A Simulation Model for the Evaluation of the Electrical Power Potential Harnessed by a Marine Current Turbine in the Raz de Sein

Rémi Balme, Karine Le Saux, Seifeddine Benelghali, Mohamed Benbouzid, Jean Frédéric Charpentier, Frédéric Hauville, Laurent Drouen

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R. Balme, K. Le Saux, S.E. Ben Elghali, *Student Member, IEEE*, M.E.H. Benbouzid, *Senior Member, IEEE*, J.F. Charpentier, *Member, IEEE*, F. Hauville and L. Drouen

***Abstract*—This paper deals with the development of a Matlab-Simulink model of a marine current turbine system through the modeling of the resource and the rotor. The purposes of the simulation model are two: performances and dynamic loads evaluation in different operating conditions and control system development for turbine operation based on pitch and speed control. In this case, it is necessary to find a compromise between the simulation model accuracy and the control loop computational speed. The Blade Element Momentum (BEM) approach is then used for the turbine modeling. As the developed simulation model is intended to be used as a sizing and site evaluation tool for current turbine installations, it has been applied to evaluate the extractable power from the Raz de Sein (Brittany, France). Indeed, tidal current data from the Raz de Sein are used to run the simulation model over various flow regimes and yield the power capture with time.**

***Index Terms*—Tidal current, marine technology, model, resource, rotor, simulation, Matlab-Simulink.**

I. Introduction

Oceans, covering more than 70 % of the earth, have long been appreciated as a vast renewable energy source. The energy is stored in oceans partly as thermal energy, partly as kinetic energy (waves and currents) and also in chemical and biological products. Numerous techniques for extracting energy from the sea have been suggested, most of which can be included in one of the following categories: wave energy, marine and tidal current energy, ocean thermal energy, energy from salinity gradients (osmosis), and cultivation of marine biomass. The kinetic energy present in marine and tidal currents can be converted to electricity using relatively conventional turbine technology. To harness the kinetic energy in waves present a different set of technical challenges and a wide variety of designs have been suggested. Ocean thermal energy conversion is possible in locations with large temperature differences, extracting energy with a heat engine. Salinity gradients can be exploited for energy extraction through the osmotic process. The cultivation of marine biomass can yield many useful products, including renewable fuels for electricity generation. However, due to technology limitations and economic considerations, osmotic and thermal energy developments are limited [1].

Only a fraction of the global ocean energy resource can be found in sites economically feasible to explore with the available technology. However, this fraction could still make a considerable contribution to electricity supply. This is the reason why the marine renewable sector is currently the focus of much industrial and academic research around the world [2]. Sites with attractive wave climate and intense tidal currents are abundant in the vicinity of the European coastline. It has been shown that 48% of the European tidal resource is in the UK, 42% in France, and 8% in Ireland [3]. There are basically two ways of generating electricity from marine and tidal currents: by building a tidal barrage across an estuary or a bay in high tide areas, or by extracting energy from free flowing water (tidal kinetic energy). Within the last few decades, developers have shifted towards technologies that capture the tidally-driven coastal currents or tidal stream. Indeed, very large amount of energy are available in coastal waters [1], [4-5]. There are many areas of the world in which extreme tidal currents are observed. Three examples in France are shown in Fig. 1. The Raz Blanchard situated in Cap de la Hague experiences extreme tidal currents exceeding 8 knots and leading to a large amount of kinetic energy flux.

It is then obvious that there is a need for quantifying the potential of generating electricity from these various sites [6]. This paper reports then on the development of a practical Matlab-Simulink simulation tool based on the modeling of the resource and the tidal turbine rotor. The BEM approach is in this case used for the turbine modeling. The proposed simulation tool has been applied to evaluate the extractable power from the Raz de Sein (Brittany, France) as it is a well-characterized site in terms of tidal current.

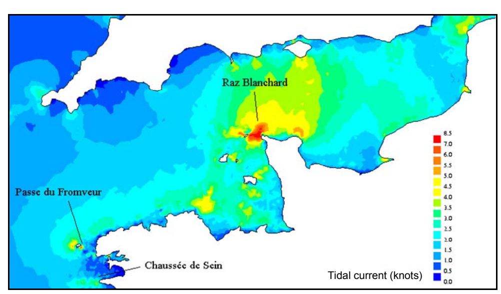

Fig. 1. Raz Blanchard, Fromveur, and Raz de Sein and sites in the French western coast.

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R. Balme*, K. Le Saux*, S.E. Ben Elghali and M.E.H. Benbouzid are with the Laboratoire d'Ingénierie Mécanique et Electrique (LIME), University of Western Brittany, Rue de Kergoat, BP 93169, 29231 Brest Cedex 3, France (e-mail: benelghali@univ-brest.fr, m.benbouzid@ieee.org). They are also with the French Naval Academy.

J.F. Charpentier, F. Hauville and L. Drouen are with the French Naval Academy Research Institute (IRENav) EA 3634, French Naval Academy, Lanveoc-Poulmic, BP 600, 29240 Brest Armées, France (e-mail: charpentier@ecole-navale.fr).

II. The Resource Modeling

The attractions of tidal currents to renewable energy developers are obvious. The medium, seawater, is more than 800 times denser than air and the astronomic nature of the underlying driving mechanism results in an essentially predictable resource, although subject to weather-related fluctuations.

As a renewable resource, tidal current flow is very predictable, to within 98% accuracy for decades. Tidal current charts are accurate to within minutes, for years ahead. The weather variations (wind, swells) deal with second order variations of the resources. Tidal current is mainly independent of prevailing weather conditions such as wind, fog, rain, and clouds that can impact other renewable generation forecasts. Solar generation is impacted by rain, clouds and fog. Wind turbines are impacted by calm weather, yet tidal cycles are as reliable as the rising of the moon. While solar and wind are valuable renewable resources, neither can be plotted with the predictability of tidal energy. Thus, reliable amounts of tidal power can be forecast with confidence. This predictability is critical to successful integration of renewable resources into the electrical grid [4].

A. Tidal Resource

The global marine current energy resource is mostly driven by the tides and to a lesser extent by thermal and density effects. The tides cause water to flow inwards twice each day (flood tide) and seawards twice each day (ebb tide) with a period of approximately 12 hours and 24 minutes (a semi-diurnal tide), or once both inwards and seawards in approximately 24 hours and 48 minutes (a diurnal tide). In most locations the tides are a combination of the semi-diurnal and diurnal effects, with the tide being named after the most dominant type. The strength of the currents varies, depending on the proximity of the moon and sun relative to earth. The magnitude of the tide-generating force is about 68% moon and 32% sun due to their respective masses and distance from earth. Where the semi-diurnal tide is dominant, the largest marine currents occur at new moon and full moon (spring tides) and the lowest at the first and third quarters of the moon (neap tides). With diurnal tides, the current strength varies with the declination of the moon (position of the moon relative to the equator). The largest currents occur at the extreme declination of the moon and lowest currents at zero declination. Further differences occur due to changes between the distances of the moon and sun from earth, their relative positions with reference to earth and varying angles of declination. These occur with a periodicity of two weeks, one month, one year or longer, and are entirely predictable [3], [7].

The resource assessment is generally based on oceanographic databases containing data with a fixed grid square resolution. The main key criteria are: maximum spring current velocity; maximum neap current velocity; seabed depth; maximum probable wave height in 50 years; seabed slope; significant wave height; and the distance from land [8-9]. For illustration, Fig. 2 shows the theoretical tidal velocity in the Raz de Sein (France) for the year 2007 and March 2007.

B. Resource Potential

The total kinetic power in a marine current turbine has a similar dependence as a wind turbine and is governed by the following equation [3], [10]

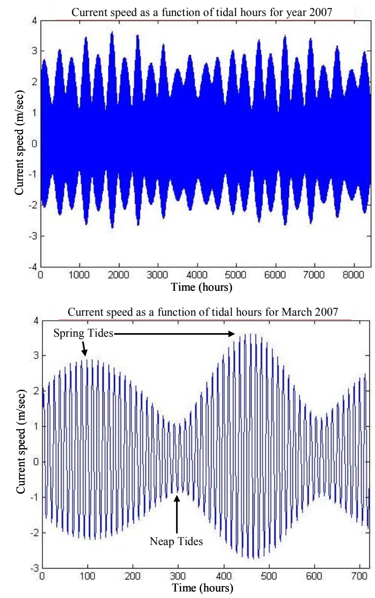


Fig. 2. Tidal velocity in the Raz de Sein for the year 2007 and March 2007.

$$P = \frac{1}{2}\rho A V_{tide}^3 \qquad (1)$$

where ρ is the fluid density, A is the cross-sectional area of the turbine and V_{tide} is the fluid velocity. However, a marine energy converter or turbine can only harness a fraction of this power due to losses and (1) is modified as follows

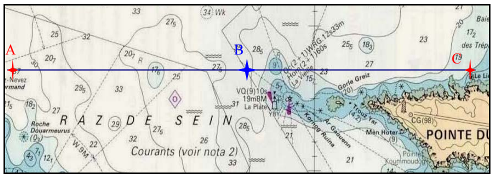
$$P = \frac{1}{2}\rho C_p A V_{tide}^3 \qquad (2)$$

C_p is known as the power coefficient and is essentially the percentage of mechanical power that can be extracted from the fluid stream by the turbine and takes into account its efficiency. This coefficient is limited to 16/27 by the well known Betz law. For wind generators, C_p has typical values in the range 0.25–0.3. The upper limit is for highly efficient machines with low mechanical losses. For marine turbines, C_p is estimated to be in the range 0.35–0.5 [11].

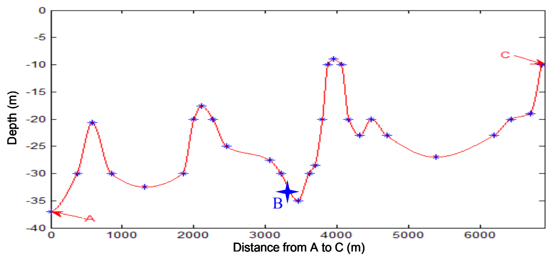
C. Resource Modeling

1) The installation site. The Raz de Sein site was chosen above several others listed in the European Commission report EUR16683 [12] due to the presence of high velocity current coupled with appropriate depths suitable for marine turbine. Moreover, the marine current velocity distribution for most of the time is greater than the minimum, estimated to be 1 m/sec, required for economic deployment of marine turbine [12-13]. The studied area is shown by Fig. 3a, where A and C are the area ends and B the marine current turbine expected installation site. Indeed, this site is located in an alternating current area where the depth is about 35 m (Fig. 3b) that will allow the installation of a marine current turbine with blades of about 20 m diameter (the maximal swell amplitude is about 10 m in this area). It should be noted that tidal current data are given by the SHOM (French Navy Hydrographic and Oceanographic Service) and is available for various location in chart form [14].

2) The resource modeling under Matlab-Simulink. Considering all the above date, the resource has been modeled at the site B that has the following GPS (WGS84) coordinates.



(a)



(b) Depth profile of the site.

Fig. 3. B: The marine current turbine expected site of installation.

$$\begin{cases} \varphi_B = 48°02'42"N \\ G_B = 004°45'45"W \end{cases}$$

The SHOM available charts give, for a specific site, the current velocities for spring and neap tides. These values are given at hourly intervals starting at 6 hours before high waters and ending 6 hours after. Therefore, knowing tides coefficient, it is easy to derive a simple and practical model for tidal current velocities V_{tide}.

$$V_{tide} = V_{nt} + \frac{(C-45)(V_{st}-V_{nt})}{95-45} \tag{3}$$

Where C is the tides coefficient (95 and 45 are respectively the spring and neap tides medium coefficient), V_{st} and V_{nt} are respectively the spring and neap tides current velocities.

This first order model is then used to calculate the tidal velocity each hour. The implemented model will allow the user to compute tidal velocities in a predefined time range. Figure 2 shows the model output for a month (March 2007) and for a year (2007). It should be noticed that the current velocity peak values will be taken into account in the choice of the marine turbine.

Figure 4 shows then the resource Simulink bloc model output according to (3) for a month (the tidal current is rectified so as not to get negative power).

3) Modeling summary. The adopted first order model for the resource has several advantages, among them, its modularity (apart from its simplicity). Indeed, the marine turbine site can be changed, the useful current velocity can be adapted, and the considered time range can also be adapted from one month to one year.

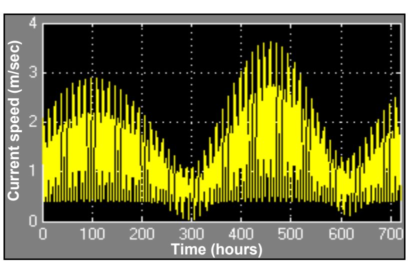


Fig. 4. Resource Simulink bloc model output.

III. The Rotor Modeling

The harnessing of the energy in a tidal flow requires the conversion of kinetic energy in a moving fluid, in this case water, into the motion of a mechanical system, which can then drive a generator. It is not too surprising, therefore, that many developers propose using technology that mirrors that which has been successfully utilized to harness the wind, which is also a moving fluid [15]. Moreover, much of the technology is based upon the use of horizontal axis turbines [16]. Therefore, much can be transferred from the design and operation of wind turbines [17]. There are, however, a number of fundamental differences in the design and operation of marine turbines. Particular differences entail changes in force loadings, immersion depth, different stall characteristics, and the possible occurrence of cavitation. Much information is however available on the cavitation and stall characteristics of marine propellers [18], which can provide a useful information for marine turbines [19-20].

A. Marine Turbine Hydrodynamics

The hydrodynamic design parameters basically entail the choice of diameter, pitch and revolutions for a particular application. Further design criteria include the pitch or twist distribution across the blade span, the stall characteristics, the blade section choice, and the need to preclude the cavitation occurrence. The hydrodynamic design is further complicated by changes in the nonuniform speed and the current direction, the shear profile in the tidal flow, and the influences of water depth and the free surface [20].

Having in mind that the simulation model purposes are two: performances and dynamic loads evaluation in different operating conditions and further control system development for turbine operation based on pitch and speed control; It is therefore necessary to find a compromise between the simulation model accuracy and the control loop computational speed. Moreover, modeling the turbine rotor is done in two steps: *1)* Performance curves evaluations that are *2)* integrated in a dynamic simulation environment.

Turbine rotor aerodynamics refers to the interaction of the wind turbine rotor with the incoming wind. The treatment of rotor aerodynamics in all current design codes is based on Glauert well-known, and well established Blade Element Momentum (BEM) theory [21]. This theory is an extension of the Rankine-Froude actuator disk model in order to overcome the unsatisfactory accuracy performance predictions based on this model.

The BEM method has therefore been used for the marine turbine rotor modeling. Indeed, it is widely used in the industry as a computational tool to predict aerodynamic loads and power of turbine rotors. It is relatively simple and computationally fast meeting the above-mentioned requirements of the simulation model [22].

B. The Rankine-Froude Actuator Disk Model [17]

In this model the rotor is replaced by an *actuator disk*, which is a circular surface of zero thickness than can support a pressure difference, and thus decelerate the tidal current through the disk. Physically, the disk could be approximated by a rotor with an infinite number of very thin, draggles blades rotating with a tip speed much higher than the tidal current velocity. The actuator disk model is thus an approximation of a real marine turbine rotor (which has only a small number of blades). As a result the flow of the actuator disk will be very different from that of a real rotor, which is unsteady, with a wake of discrete vorticity corresponding to the discrete loading.

The principal use of the actuator-disk model is to obtain a first estimate of the wake-induced flow, and hence the total induced power loss. Note that the actual induced power loss will be larger than the actuator-disk result because of the nonuniform and unsteady induced velocity. The assumptions on which the Rankine-Froude actuator disk theory is based are well-detailed in [23]. Among these assumptions, one requires that the disk slows the tidal current equally at each radius, which is equivalent to assuming uniform thrust loading at the disk. Uniform thrust loading is, in turn, equivalent to considering an infinite number of rotor blades.

For a turbine with zero loading, the current velocity in the rotor plane (V_r) is equal to the undisturbed tidal current velocity (V_{tide}), while an operating and hence loaded turbine slows down the current velocity to a lower value. If the velocity decrease induced by the rotor is V, then the velocity at the disk is $V_{tide} - V = V_r$, while far downstream at section 1 the current has been slowed further to velocity V_∞. The difference between the axial component of the current velocity and the axial flow velocity in the rotor plane is usually called the *induced* velocity.

Thus, the velocity at the disk is the average of the upstream and downstream velocities. Defining an axial induction factor, a, as the fractional decrease in current velocity between the free stream and the rotor plane represented by

$$a = \frac{V}{V_{tide}} \tag{4}$$

It follows that
$$\begin{cases} V_r = V_{tide}\left(1-a\right) \\ V_\infty = V_{tide}\left(1-2a\right) \end{cases} \tag{5}$$

For $a = 0$, the current is not decelerated and no power is extracted, whereas for $a = 0.5$, the far wake velocity vanishes, and, without presence of flow behind the turbine, no power is generated.

The power extracted from the tidal current by the rotor is given by

$$P = \frac{1}{2}\rho A V_r \left(V - V_\infty\right)\left(V + V_\infty\right) \tag{6}$$

Substituting V_r and V_∞ from (5), we find that

$$P = \frac{1}{2}\rho A V_{tide}^3 4a\left(1-a\right)^2 \tag{7}$$

A power coefficient C_p is then defined as

$$C_p = \frac{P}{\frac{1}{2}\rho A V_{tide}^3} = 4a\left(1-a\right)^2 \tag{8}$$

where the denominator represents the kinetic energy of the free-stream current contained in a stream tube with an area equal to the disk area.

The maximum value of the power coefficient C_p occurs when $a = 1/3$. Hence, $C_{p,max} = 16/27 \approx 0.59259$, $V_r = ⅔V_{tide}$, and $V_\infty = ⅓V$. Thus the maximum amount of energy extraction equals the 16/27th part of the kinetic energy in the current. This limit is often referred to as the *Betz limit*, or more accurately the *Lanchester-Betz limit*.

Additional data that can be derived from this model include the thrust loading on the rotor.

$$D_r = \frac{1}{2}\rho A\left(V_{tide}^2 - V_\infty^2\right) = \frac{1}{2}\rho A V_{tide}^2\left[4a\left(1-a\right)\right] \tag{9}$$

Moreover, if this thrust loading is considered as a drag force on the rotor, we can define a drag coefficient as follows.

$$C_{dr} = \frac{D_r}{\frac{1}{2}\rho A V_{tide}^2} = 4a\left(1-a\right) \tag{10}$$

Since a flat plate has a drag coefficient of about 1.28, we can note that, for $a = 1/3$, we obtain an equivalent drag coefficient of 8/9 for a rotor operating at the maximum C_p condition. Thus the rotor thrust is about 30% less than that of a flat plate equal in diameter to the rotor. Therefore, it is easy to see that the thrust loads generated by continuing to operate in high currents can be very large, requiring a very strong rotor and tower.

C. The BEM Model

BEM theory is one of the oldest and most commonly used methods for calculating induced velocities on wind turbine blades. This theory is an extension of the above studied actuator disk theory. BEM theory assumes that blades can be divided into small elements that act independently of surrounding elements and operate hydrodynamically as two-dimensional airfoils whose hydrodynamic forces can be calculated based on the local flow conditions. These elemental forces are summed along the span of the blade to calculate the total forces and moments exerted on the turbine. The other half of BEM, the momentum theory, assumes that the loss of pressure or momentum in the rotor plane is caused by the work done by the fluid flow passing through the rotor plane on the blade elements. Using the momentum theory, one can calculate the induced velocities from the momentum lost in the flow in the axial and tangential directions. These induced velocities affect the inflow in the rotor plane and therefore also affect the forces calculated by blade element theory. This coupling of two theories ties together blade element momentum theory and sets up an iterative process to determine the hydrodynamic forces and also the induced velocities near the rotor.

In practice, BEM theory is implemented by breaking the blades of a marine turbine into many elements along the span. As these elements rotate in the rotor plane, they trace out annular regions across which the momentum balance takes place. These annular regions are also where the induced velocities from the wake change the local flow velocity at the rotor plane. BEM can also be used to analyze stream tubes through the rotor disk, which can be smaller than the annular regions and provide more computational fidelity [22], [24].

The contribution of each blade element to the lift and drag force can be derived as follows. Consider an annular cross-section of a rotor blade as depicted in Fig. 5, and examine an element of length Δr of one blade.

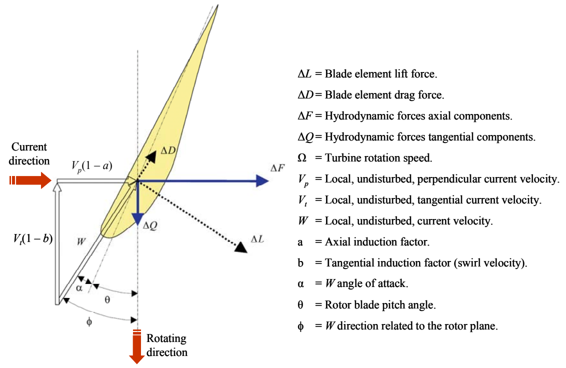


Fig. 5. Blade element velocities and hydrodynamic forces in the blade local coordinate frame with the chord line as reference.

The net effect on current flowing through this annular section of the rotor disk results from the forces and moments on all the blades. The instantaneous relative undisturbed water velocity experienced by a blade element is

$$W = \sqrt{\left[V_p\left(1-a\right)\right]^2 + \left[V_t\left(1+b\right)\right]^2} \tag{11}$$

Under an angle $\phi = \arctan\left(\dfrac{V_p\left(1-a\right)}{V_t\left(1+b\right)}\right)$ (12)

It must be noted that the tangential induction factor b in the above equation is as a rule an order smaller than the axial induction factor a [17].

Due to the resultant velocity W the blade cross-section exerts a quasi-steady hydrodynamic lift force.

$$\Delta L = \frac{1}{2}\rho c W^2 C_L \Delta r \tag{13}$$

and a quasi-steady hydrodynamic drag force.

$$\Delta D = \frac{1}{2}\rho c W^2 C_D \Delta r \tag{14}$$

where c is the local blade chord, C_L is the blade element 2D lift coefficient, C_D is the blade element 2D drag coefficient, and Δr is the blade section length. The dimensionless hydrodynamic coefficients C_L and C_D – among other things – are functions of the attack angle α and the Reynolds number.

The axial induced velocity can be determined by expressing the axial thrust ΔF on a blade element as the rate of change of momentum in the annular ring swept out by this element. On the other hand, the tangential induced velocity can be determined by expressing the torque ΔQ on a blade element as the rate of change of angular momentum.

$$\begin{cases} \Delta F = 4\rho\pi r V_p^2 a\left(1-a\right)\Delta r \\ \Delta Q = 4\rho\pi r^2 V_t V_p b\left(1-a\right)\Delta r \end{cases} \tag{15}$$

The above equations will lead to the calculation of both axial and tangential coefficient.

$$\begin{cases} a = \dfrac{\sigma_r C_N}{4\sin^2\phi + \sigma_r C_N} \\ b = \dfrac{\sigma_r C_T}{4\sin\phi\cos\phi - \sigma_r C_T} \end{cases} \tag{16}$$

With $\begin{cases} C_N = C_L\cos\phi + C_D\sin\phi \\ C_T = C_L\sin\phi - C_D\cos\phi \end{cases}$ and $\sigma_r = \dfrac{N_b c}{2\pi r}$

where N_b is the blade number and σ_r is the chord solidity.

Because of its simplicity, the BEM theory does have its limitations. To overcome the restricting assumptions of the above briefly described BEM method, in state of the art aeroelastic codes for wind turbines, a number of semi-empirical corrections are applied [22]. Two corrections have been adopted for the proposed simulation model. The first one takes into account the so-called blade tip and root effects. In this case, (16) becomes

$$\begin{cases} a = \dfrac{\sigma_r C_N}{4F_L\sin^2\phi + \sigma_r C_N} \\ b = \dfrac{\sigma_r C_T}{4F_L\sin\phi\cos\phi - \sigma_r C_T} \end{cases} \tag{17}$$

where F_L is Prandtl combined blade tip and blade root loss factor.

The second correction concerns the *turbulent wake state*. In this case, we have adopted the Glauert empirical relation [23].

$$a = 0.143 + \sqrt{0.6427 C_{dr} - 0.55106} \tag{18}$$

for $C_{dr} > 0.96$.

D. Rotor Design Options

The choice of 3 blades was made after considering both 2 and 3 blade options. Rotors with 3 blades have the advantage of being slightly more efficient, and they are also more balanced, inducing less fatigue load on the gearbox and the structure. The orientation of the rotor is fixed, but the blades can be pitched through 180° so that it can be used for currents in both directions, either on the ebb or the flood tide. The turbine rotor can be changed from operating on a flood tide to an ebb tide simply by reversing the blades, pitching them through 180°. The ability to pitch also meant that the blade angle could be optimized in any given current, the blades could be feathered to brake the rotor gently, and the maximum power generated could be limited by angling the blades away from the optimum position. It was therefore decided to implement full-length blade pitch control (Fig. 6). For this turbine, we have adopted the NACA 44 profile shape [13].

E. Validation of the Proposed Model

For validation purposes, we have compared the simulation model to experimental data from the available literature [19-25]. Indeed, the first simulated marine turbine corresponds to the one tested in [25]: For a 0.8 m model of a marine current turbine, a current velocity $V_{tide} = 1.5$ m/sec, and a pitch angle $\theta = 25°$; a C_p of about 0.32 was found in comparison to 0.36 in the tank test.

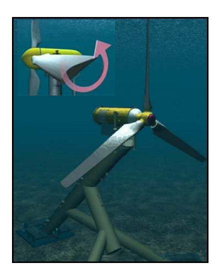


Fig. 6. The 3 (E-tide) blades options [© Strøm AS].

F. Simulation Results in the Raz de Sein

For the Raz de Sein site, the maximum current velocity is about 3.63 m/sec for 2007. We have then adopted a ratio of 75% for economically viable operation of the marine turbine [12]. This leads to a turbine rotor design with 2.72 m/sec for optimal operation. Moreover, simulations are based on marine turbine with blades of 17.4 m diameter and of 1 MW net electric power. In this context, the obtained power coefficient C_p curves are shown by Fig. 7.

Now, the whole simulation tool is used including the resource and the rotor models. The tool input data are those corresponding to optimal operation (V_{tide} = 2.72 m/sec). The expected output power of the turbine rotor is about 1.108 MW taking into account the gearbox and the generator efficiencies. In this simulation context, the obtained results are shown by Figs. 8 and 9. They are very promising. Indeed, two relevant points are noticed: The maximum output power is about 1.13 MW leading to a relative error of 2%. Moreover, it is well-known that the adopted marine current turbine cannot produce power from water current flow as low as 1 m/sec. This is well illustrated by Fig. 9.

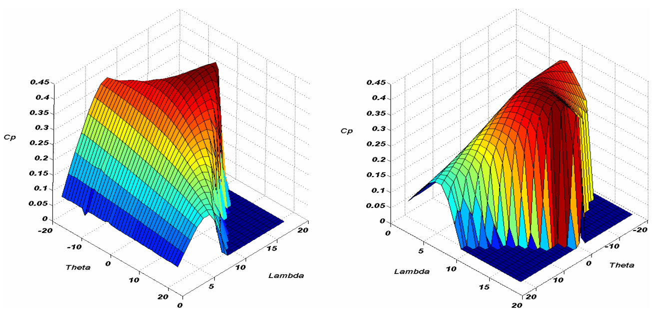


Fig. 7. C_p (λ,θ) curves.

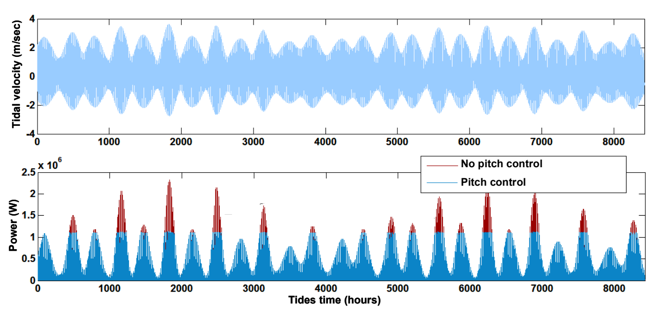


Fig. 8. The estimated extracted power for year 2007.

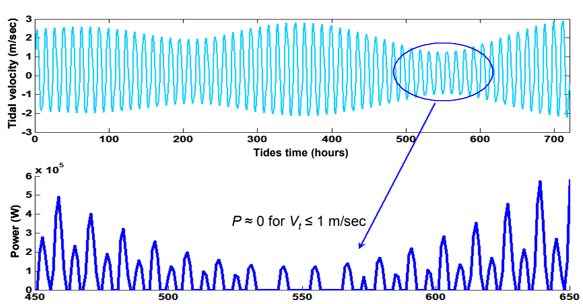


Fig. 9. The estimated extracted power for July 2007.

IV. Conclusion

This paper has proposed a Matlab-Simulink based simulation tool for marine current turbines through the modeling of the resource and the rotor. In this case the Blade Element Momentum (BEM) approach has been used for the turbine modeling. A part of the proposed simulation tool has been validated according to the rare experimental results available in the literature. It has then been applied to evaluate the extractable power from the Raz de Sein (Brittany, France). The obtained results are consistent and very promising.

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